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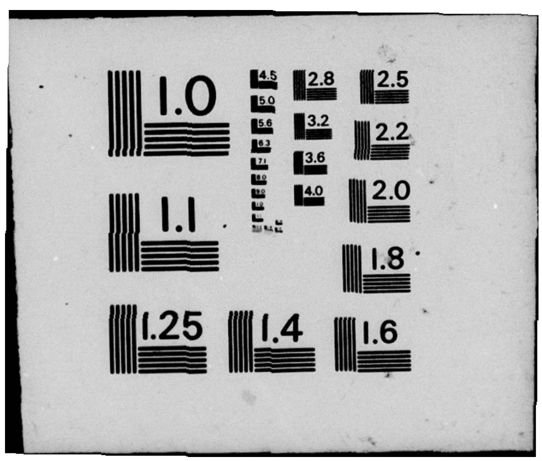
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# ENGINE PERFORMANCE AND FIRE-SAFETY CHARACTERISTICS OF WATER-CONTAINING DIESEL FUELS

**INTERIM REPORT**
**AFLRL NO. 83**

12

by

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under contract to

**U.S. Army Mobility Equipment Research and Development Command**
**Energy and Water Resources Laboratory**
**Fort Belvoir, Virginia**

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December 1976

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| Engine Performance | Smoke | Fire Resistant Combat Fuel |
| Fire-Safety Fuels | Diesel Smoke Reduction | |
| Water/Oil Emulsion | Antimist Fuel | |

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)


Recent flammability evaluations conducted at U.S. Army Fuels and Lubricants Research Laboratory (AFLRL) have shown that water-containing diesel fuels are more fire resistant (even at temperatures above the flash point) than the same fuel without the water added. These findings led to this project to evaluate the compatibility of such fuels with a full scale diesel engine. → CONT.


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20. ABSTRACT (Cont'd)

Blends of base diesel fuel plus 2-percent emulsifying agent plus as much as 10-percent water were evaluated in an unmodified LDT-465-1C, a multifuel diesel engine with wide field usage. No significant changes were observed in power output when operating the engine at equal base fuel flow rates. The smoke-reduction effects were inconclusive, but the nonvisible emissions were substantially altered. Oxides of nitrogen emissions were decreased as much as 30 percent but were accompanied by a 250-percent increase in unburned hydrocarbons. The conclusion followed that potential fire-safety benefits and a lack of major detrimental effects in the engine make these water/fuel blends attractive candidates for fire-resistant combat fuels.

## FOREWORD

This work was conducted at the U.S. Army Fuels and Lubricants Research Laboratory located at Southwest Research Institute, San Antonio, Texas, under Contract No. DAAG53-76-C-0003 during the period June 1976 through August 1976. The work was funded by U.S. Army Mobility Research and Development Command (USAMERADCOM), Energy and Water Resources Laboratory, Ft. Belvoir, Virginia. The contract monitor was Mr. F.W. Schaekel, USAMERADCOM, DRDME -GL, Ft. Belvoir, Virginia.

Acknowledgment is given to Mr. L.D. Sievers who supervised the engine tests and Messrs. J. Kachich and J.P. Pierce who blended the various emulsified fuels and conducted the ballistics experiments. Acknowledgment is also given to Messrs. R.D. Quillian, Jr., A.A. Johnston, S.J. Lestz, and Dr. W.D. Weatherford, Jr. for their encouragement and suggestions.

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# I. INTRODUCTION

## A. Background

Periodically throughout the development of the internal combustion engine, various methods have been developed to introduce water as a fuel additive in response to problems that have arisen. Through the years, water has been proposed as a knock suppressant[1,2]*, an internal (in the combustion chamber) coolant[2,3], an oxide's of nitrogen suppressor[2,4,5,6,8], and a combustion improver[1,7] with varying degrees of success. The majority of these uses have been based on water functioning as an internal heat sink, using the heat of vaporization to reduce combustion temperatures. And in most cases, the water has been inducted through the intake system of a spark ignition engine.

Recently, interest has shifted toward the blending of fuel and water into a single fluid. This blending of two normally immiscible compounds has been accomplished by the use of surfactants. These water/fuel emulsions can be handled by standard (or only slightly modified) fuel delivery systems.

Perhaps the most interesting aspect of these water/fuel emulsions was recently discovered at AFLRL, this being their resistance to burning, except under overwhelming ignition conditions such as in a combustion chamber. Ballistic tests conducted at AFLRL using 20-mm high-explosive incendiary tracer projectiles have shown a definite resistance to total pool burning of these fuels, even at temperatures 14°C (25°F) above the fuel's flash point. The significance of this is the fact that when the fuel tank of a tactical ground-equipment vehicle is subjected to ballistic penetration, quite often the result is total conflagration, resulting not only in loss of life, but rendering the vehicle totally nonsalvageable. One means of reducing the fire vulnerability of tactical ground vehicles is the use of a fire-safety fuel such as this water-containing heat-sink fuel.

The exact mechanism explaining how the emulsion actually reacts in an engine has been the object of considerable research and conjecture in recent years. One theory that has been advanced recently is the theory of microexplosions.[9,12,13] In a normal water/oil emulsion, small water droplets are suspended within much larger fuel-oil droplets in the fuel. When the fuel is heated, as during the injection/preflame period in a diesel engine, the fuel temperature passes through the boiling point of water, whereupon the water droplets vaporize within the liquid fuel oil droplets. This causes the fuel droplets to literally explode, thereby breaking into smaller, more easily burned particles. This could lead to more complete combustion and a higher combustion rate.

A number of researchers have attempted to apply this microexplosion technique to diesel engines to improve combustion or reduce visible smoke. Valdmanns and Wulfhorst[10] have shown that water/fuel emulsions containing from 20- to 50-percent (vol) water produced a slight increase in indicated mean effective pressure (IMEP) while reducing both smoke and oxides of nitrogen ($NO_x$) emissions. However, the water caused such a large increase in the ignition delay period that the required advance of injection timing masked the water effects.

## B. Objective

This brief project was conducted to assess the performance advantages and penalties when using a water-containing fuel in the LDT-465-1C multifuel diesel engine and to evaluate the fire-safety characteristics of such fuels. Particular attention was to be given to effects on engine power output, specific fuel consumption, smoke and emissions, using an unmodified engine.

*Superscript numbers in parentheses designate references at end of report.

## II. EXPERIMENTAL

### A. Preparation of Water/Oil Emulsions

Two different emulsions were prepared using the same base fuel and surfactants, but with water concentrations of 5 percent (vol) and 10 percent (vol). The HLB (hydrophile-lipophile balance) of the emulsifiers was adjusted to approximately 5.4 by a combination of Span 80 and Tween 80. This ratio falls within the range generally considered optimum for preparing a water-in-oil emulsion.

The ingredients were pre-blended in a stainless vat constantly stirred by an air-driven motor. This blend was pumped through an ultrasonic homogenizer at the rate of approximately 1 liter per minute. The water droplet size was monitored, by microscope, and then the various homogenizing parameters were adjusted to give droplets in the range 1 to 5 microns. Although the exact stability of the emulsions was not exactly defined, they did remain stable throughout the series of engine tests. In addition to the ultrasonic homogenizer, a mechanical mixing unit was used to blend one batch of fuel. This unit was a multiple pass piston-type homogenizer.

TABLE 1. LDT-465-1C CHARACTERISTICS

| | |
|---|---|
| No. of Cylinders | 6 |
| Bore, cm (in.) | 1.80 (4.56) |
| Stroke, cm (in.) | 1.92 (4.87) |
| Displacement, l($in^3$) | 7.83 (478) |
| Compression Ratio | 22:1 |
| Fuel Injection System | Bosch Rotary Distributor with density compensation |
| Turbocharger | 3-in. Schwitzer |
| Piston Type | Annulus |

TABLE 2. TEST DIESEL FUEL BLENDS

| Fuel Code | AL-6374 | 2-Percent Emulsion | 5-Percent Water | 10-Percent Water |
|---|---|---|---|---|
| Gravity, °API @ 60° F | 33.9 | 32.7 | 31.4 | 30.1 |
| Kinematic Viscosity @ 38° C (100° F), cSt | 3.38 | 3.65 | 3.7 | 4.62 |
| Flash Point, °C (°F) | 63 (146) | 66 (150) | 66 (150) | 70 (158) |
| Aniline Point, °C (°F) | 64 (147) | — | 80 (176) | 94 (201) |
| Total Acid Number, mg KOH/g | 0.006 | — | — | — |
| Karl Fischer Water, % | 0.026 | — | — | — |
| Distillation, D86,° C (° F) | | | | |
| IBP | 151 (303) | — | — | — |
| 5% | 207 (405) | — | — | — |
| 10% | 242 (468) | — | — | — |
| 20% | 261 (502) | — | — | — |
| 50% | 284 (544) | — | — | — |
| 90% | 340 (644) | — | — | — |
| 95% | 360 (680) | — | — | — |
| FBP | 370 (698) | — | — | — |
| Percent Recovered | 99.0 | — | — | — |
| Cetane No. | 50.5 | 48.3 | 45.2 | 42.8 |
| Existent Gum, mg/100 ml | 4.5 | — | 1400 | 1570 |
| Total Sulfur, wt % | 0.056 | — | — | — |
| Gross Heat of Combustion, kj/kg (BTU/lb) | 45,100 (19,390) | 44,820 (19,270) | 42,570 (18,300) | — |
| Percent Saturates by HPLC | 64.4 | — | — | — |
| Percent Aromatics by HPLC | 35.6 | — | — | — |
| Percent Olefins | 0 | — | — | — |

### B. Test Engine

The engine chosen for this work was the LDT-465-1C, a six-cylinder, 7.83-liter (478 $in^3$) turbocharged diesel engine with wide military field application. The general characteristics are given in Table 1. The engine was used as received without modification to the injection pump or timing. The fuel injection pump used with this engine is equipped with a density compensator which varies the full rack fuel delivery rate as a function of fuel density. This system was left intact and, as a result, the full rack engine data are in some instances altered from what would normally be expected.

The characteristics of the diesel fuel used are given in Table 2. The water used for the fuel blends was totally deionized.

### C. Engine Test Technique

The various test fuels were blended in 204-liter (54-gal.) batches and transferred to the fuel system. The engine data were taken by stabilizing the engine at constant speed while operating on the base fuel, then switching to the test fuels, concluding with the base fuel. In this way, all the fuels were evaluated at as close to the same condition as possible. All the test points were chosen so that the same base fuel flow rate was obtained. Therefore, all the data were obtained at the same diesel fuel flow rate, regardless of the actual volume of total fuel being consumed in the engine, since the total fuel consists of the base diesel fuel and 2-percent emulsifying agent plus from 5- to 10-percent water.

### D. Ballistic Evaluation Technique

These ballistic tests comprised the firing of 20-mm High Explosive Incendiary Tracer (HEIT) projectiles horizontally into the face of 114-liter (30-gal.) drums containing 76 liters (20-gal.) fuel. A tilted (45°) aluminum plate, 0.6 cm (1/4 in.) thick, was mounted with its center 30 cm (1 ft) in front of the drum face. The 20-mm projectile (velocity approximately 1000 m/sec) struck the actuator plate and hit the center of the drum face just below the liquid level. The ballistic penetration and resulting fireball were recorded on video tape and 16-mm color film (24 frame/sec and 800 frame/sec).

## III. DISCUSSION

One of the first questions to be answered when contemplating using water-containing diesel fuels is the effect the water has on the cetane number. The results of cetane determinations with varying water concentrations are shown in Figure 1 where, as would be expected, water lowers the cetane number. Notice too that the emulsifier alone reduced the cetane number by 2 points. This is a consequence of the particular emulsifier chosen, and other acceptable emulsifying agents could probably be used which would improve the cetane number of the base fuel and therefore partially compensate for the effects of the water.[12] Although the engine was normally started using the base diesel fuel and the motor in the dynamometer, a startability check was made using the engine starter and the 10-percent water blend. With both the ambient air and water jacket at 27°C (80°F), the engine started normally. (However, the idle speed was lower than normal due to the reduced diesel fuel volume in each injection.)

As shown in Figures 2 through 4 for the same diesel fuel flow rates, there was no loss in performance with either water blend. However, notice that there appears to be a slight increase in power with the fuel containing only the emulsifying agent. This is due to the fact that the analysis assumed that only the base fuel contributed to the combustion process. However, the emulsifying agent is also combustible and has a calculated higher heating value of 34,900 kilojoules/kg (15,000 BTU/lb). Thus it appears that the water

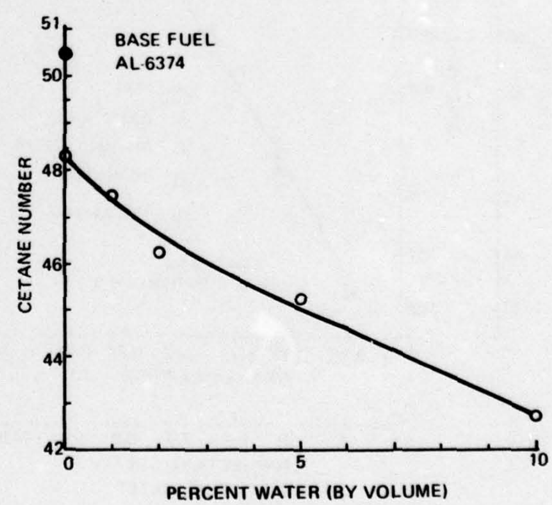



FIGURE 1. EFFECTS OF WATER CONTENT ON CETANE NUMBER

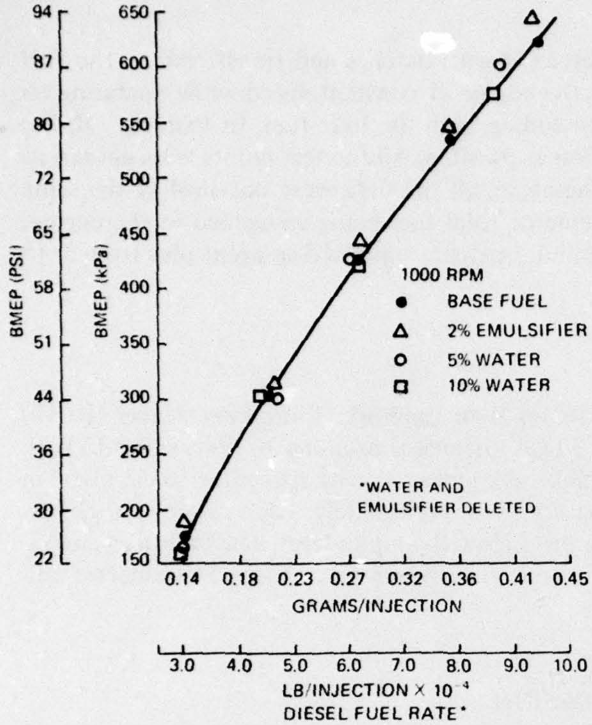



FIGURE 2. EFFECTS OF WATER EMULSIONS ON BMEP–1000 RPM

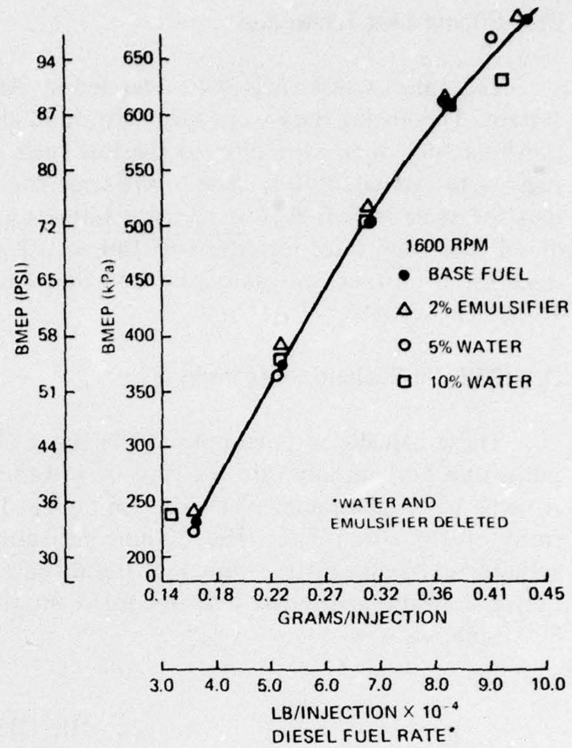



FIGURE 3. EFFECTS OF WATER EMULSIONS ON BMEP–1600 RPM

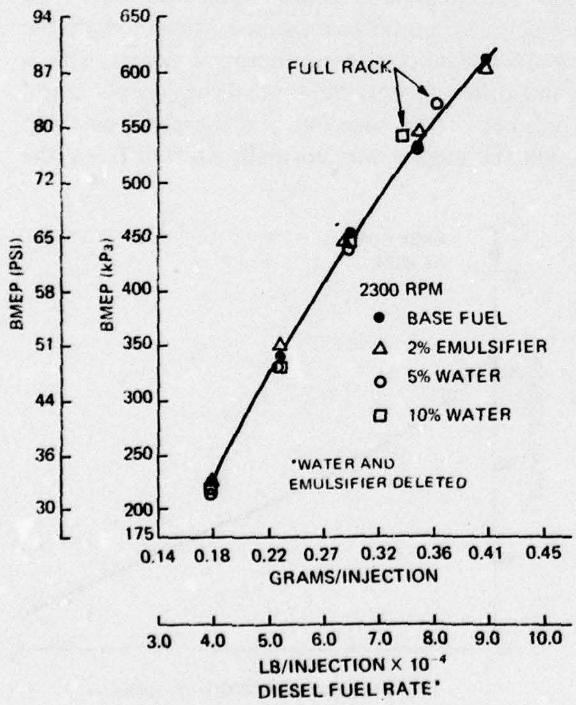



FIGURE 4. EFFECTS OF WATER EMULSIONS ON BMEP–2300 RPM

blends do cause a slight loss in performance, but the heat added by the emulsifying agent compensates for this loss. The emulsions do not cause a significant change in power, except at full rack, where the injection pump limits the total volume of fuel that can be injected. Because of this fuel limit at full rack settings plus the changes in delivery volume caused by the density compensator, much of the full rack data are modified from the expected results. The more extreme of these have been noted on the various figures.

As the power data indicate, one would not expect to see a significant change in specific fuel consumption, and this was the case. However, there are two methods of determining specific fuel consumption with these heat sink fuels. A vehicle operating on an emulsified fuel would "see" the total fuel, and as a result the specific fuel consumption of total fuel would be the important parameter. As seen in Figures 5 through 7, when the total fuel usage is considered, the specific

consumption of the 5- and 10-percent water blends is significantly higher, as would be expected. The 5-percent water blend increases the specific consumption by approximately 7 percent and the 10-percent blend increased consumption by 12 percent. Thus, a vehicle using the 5-percent water blend would either have a 7-percent reduction in range or require a larger fuel tank. Apparently the emulsifier, even though its heat of combustion is 77 percent of that of the diesel fuel, contributes very little to the combustion process when water is present or the water causes a greater percentage performance loss than its concentration indicates. In the latter case then, the heat supplied by the emulsifying agent coincidentally offsets this additional power loss.

When specific fuel consumption is expressed in terms of the base diesel fuel only, Figures 8 through 10, the effects of water emulsions as a fuel extender can be seen. Once again, the combustible emulsifying agent's effect can be seen, but as before, there does not appear to be a significant penalty or benefit from the water emulsions. Therefore, the two water emulsions tested do not appear to function as fuel extenders under the conditions of these experiments.

Another possible advantage with emulsified water/diesel fuel blends is the possibility of significant reductions in visible smoke. This could be of significant interest in combat equipment if vehicle signature could be reduced. Work with gas turbine engines have

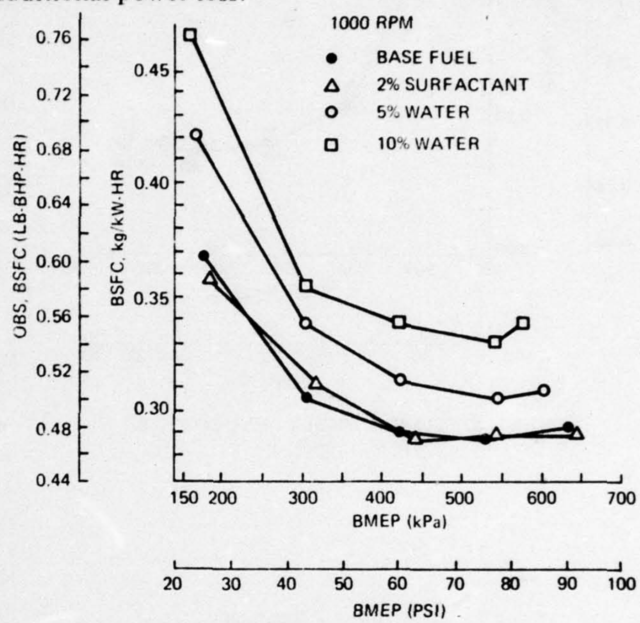



FIGURE 5. SPECIFIC CONSUMPTION OF TOTAL FUEL–1000 RPM

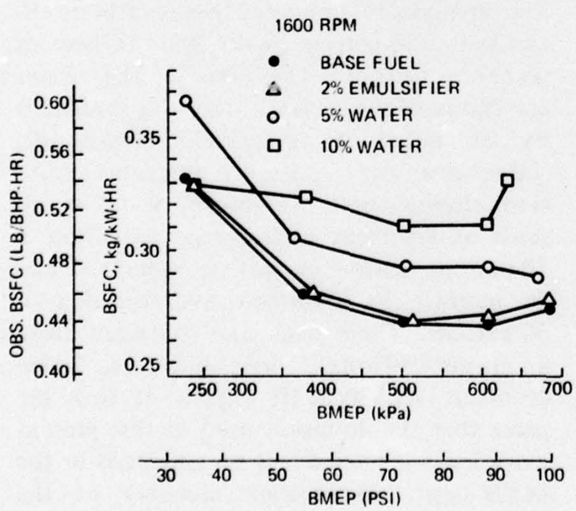



FIGURE 6. SPECIFIC CONSUMPTION OF TOTAL FUEL–1600 RPM

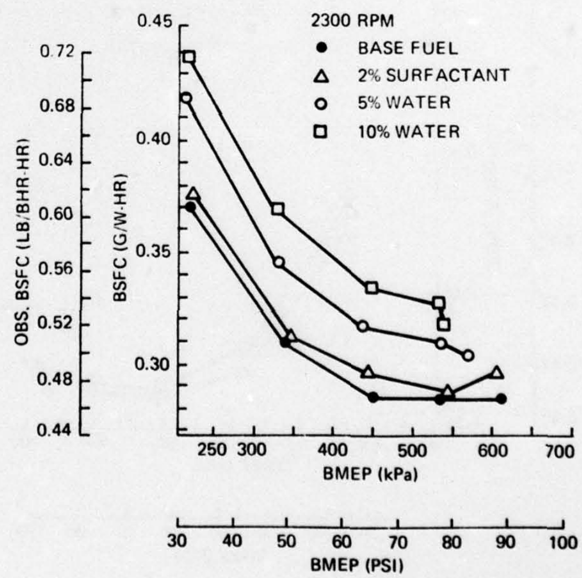



FIGURE 7. SPECIFIC CONSUMPTION OF TOTAL FUEL–2300 RPM

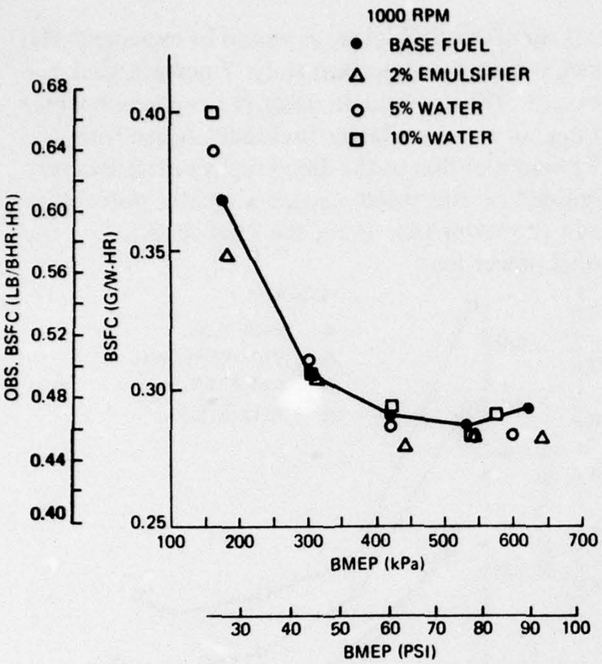



FIGURE 8. SPECIFIC DIESEL FUEL CONSUMPTION–1000 RPM

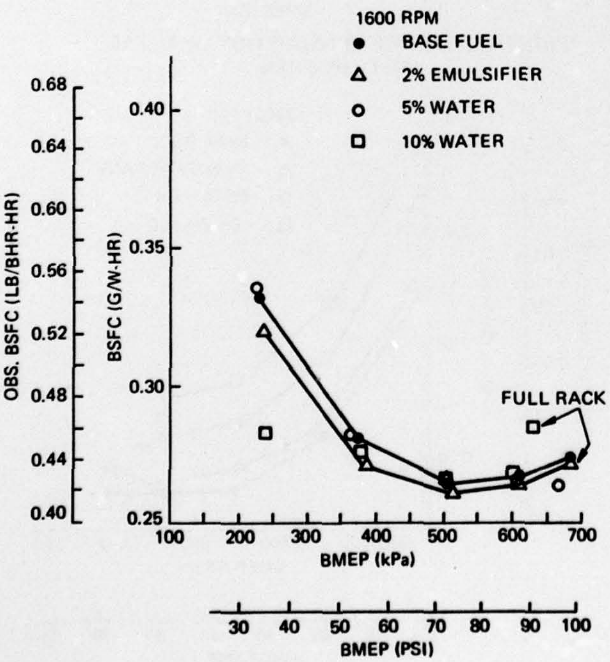



FIGURE 9. SPECIFIC DIESEL FUEL CONSUMPTION–1600 RPM

demonstrated smoke reductions with water emulsions[11], and this work has shown the possibility of a reduction in smoke. Figure 11 shows the variation of smoke output with load at 1000 RPM, and it appears that the emulsions do reduce the smoke production. However, also note that the emulsifier alone had as large an effect as either water-containing fuel. Figure 12 shows the results at higher engine speeds where it appears that any effects the water may have diminish with increasing speed. These smoke-reduction effects require more extensive study before more definite conclusions can be drawn, but the initial reductions under low-speed, high-smoke conditions appear promising.

The use of inducted water to reduce oxides of nitrogen is well documented.[4,5] The water acts as an inert material which lowers the peak combustion temperatures. The water-containng emulsions have the same effect as shown in Figures 13 to 16. As the water content increases, the $NO_x$ emission decreases. Average reduction in $NO_x$ with 10-percent water is approximately 25 percent. However, as the water reduces the peak combustion temperatures to reduce $NO_x$, it also reduces the extent of hydrocarbon combustion, resulting in increased unburned hydrocarbon emissions. The increase in unburned hydrocarbons exceeded 250 percent with the 10-percent water emulsion (Figure 17). The water emulsions also increased the CO emissions by as much as 25 percent (Figure 18). Valdmanns and Wulfhorst indicated emission changes with 10-percent water emulsions of 8-percent nitric oxide reduction, a 10-percent carbon monoxide reduction and an increase in unburned hydrocarbons of 50 percent. Their data were obtained from a single-cylinder, direct-injection, open-chamber, ALV-type III engine. It thus appears that the emulsion used in this present work has a greater effect on emissions or the MAN-type combustion chamber of the LDT-465-1C engine is more sensitive to the water contained in the fuel, or both.

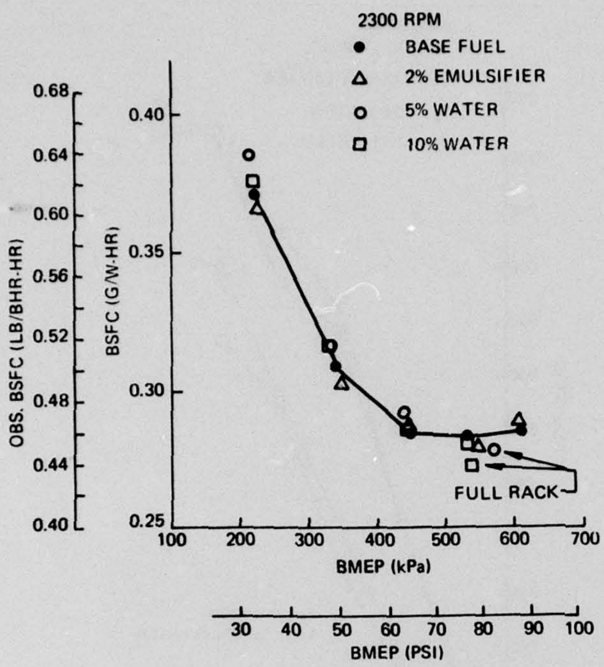



FIGURE 10. SPECIFIC DIESEL FUEL CONSUMPTION–2300 RPM

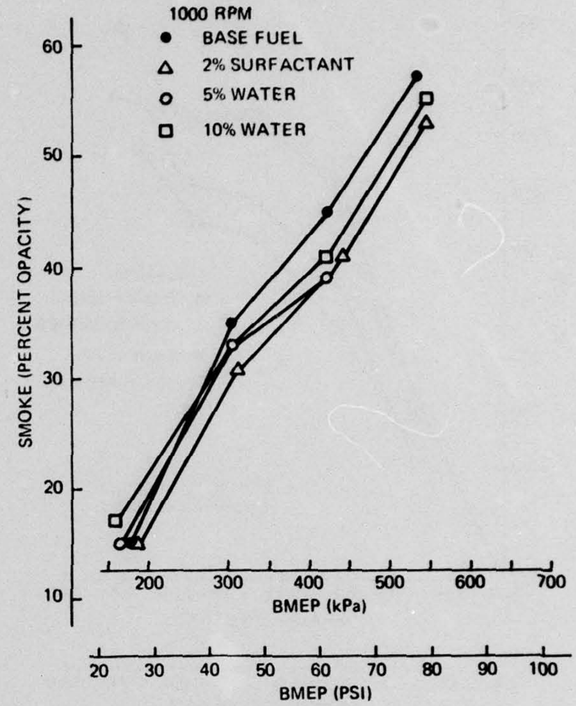



FIGURE 11. WATER EMULSION EFFECTS ON EXHAUST SMOKE–1000 RPM

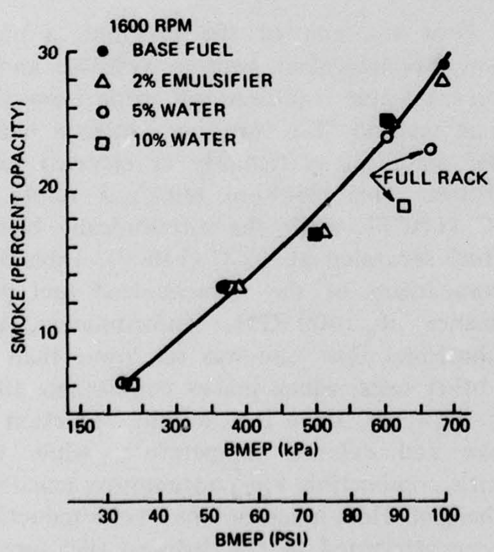



FIGURE 12. WATER EMULSION EFFECTS ON EXHAUST SMOKE–1600 RPM

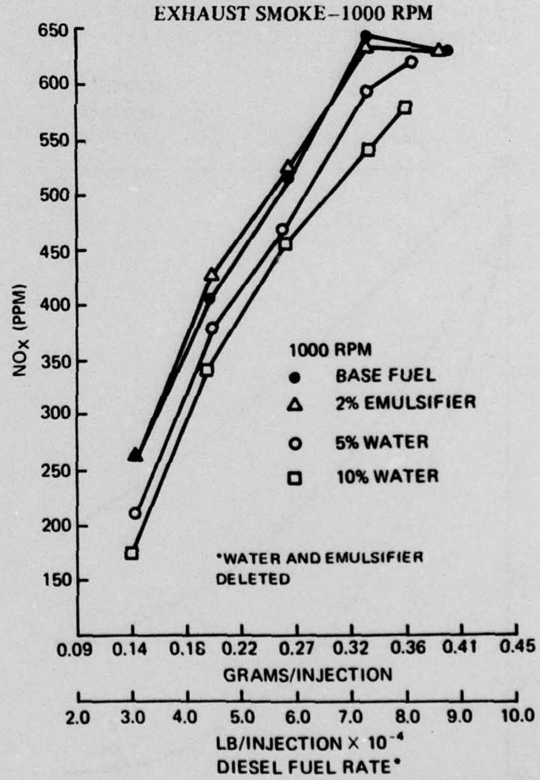



FIGURE 13. EFFECTS OF WATER EMULSIONS ON NITROGEN OXIDES EMISSIONS–1000 RPM

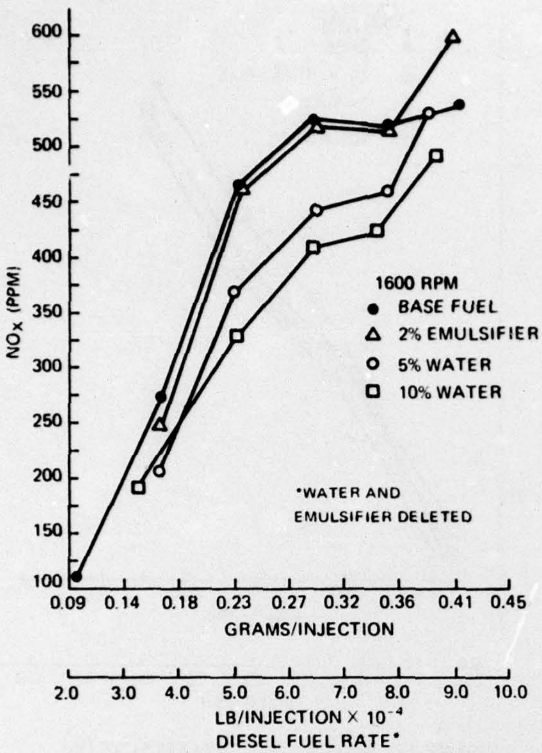



FIGURE 14. EFFECTS OF WATER EMULSIONS ON NITROGEN OXIDES EMISSIONS–1600 RPM

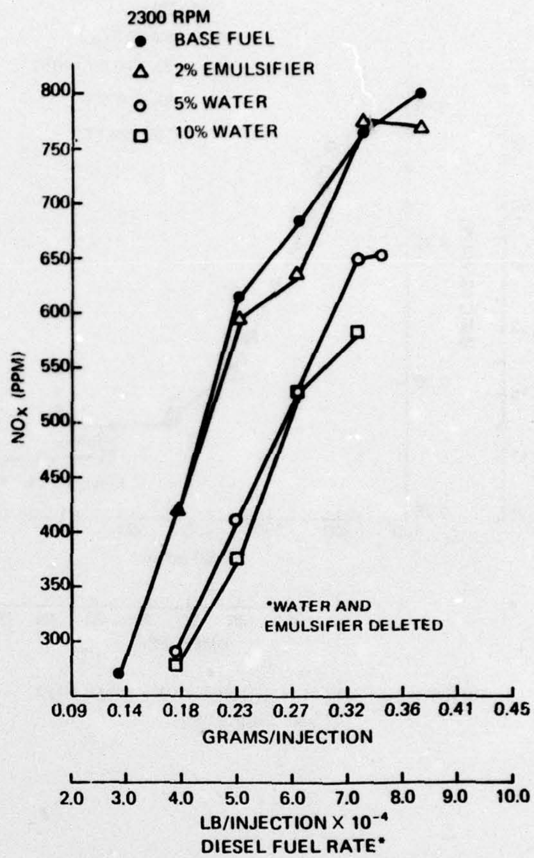



FIGURE 15. EFFECTS OF WATER EMULSIONS ON NITROGEN OXIDES EMISSIONS–2300 RPM

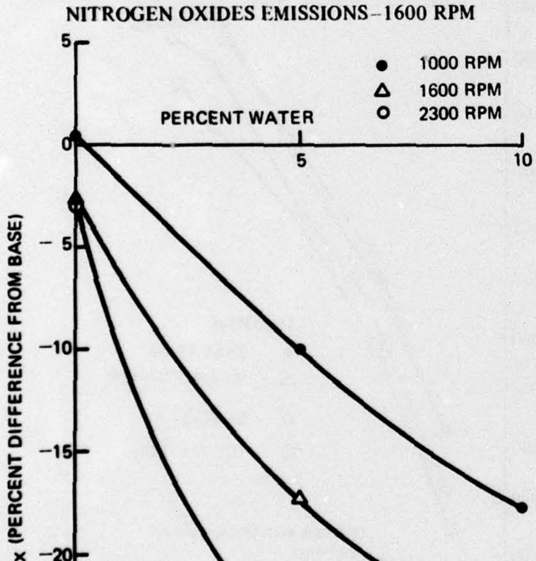



FIGURE 16. PERCENT CHANGE IN NITROGEN OXIDES EMISSIONS WITH WATER CONTENT

Near the end of the program, a high-pressure homogenizer became available and a 5-percent water emulsion was made using this mixing method. The resulting emulsion had a better stability, particularly at elevated temperatures. This emulsion remained stable at 77°C (170°F), while the ultrasonically blended fuel separated at 66°C (150°F). Table 3 is a comparison of the homogenized fuel performance at 1600 RPM. Unfortunately, the combustibles flow rate was set lower than in the other tests, which makes comparison difficult. However, there is a definite reduction in smoke and exhaust temperature, while the specific combustible fuel consumption remained unchanged. How much of this smoke reduction can be attributed to the reduced fuel rate is unknown. Unfortunately, there was insufficient fuel for further testing.

TABLE 3. INFLUENCE OF FUEL/WATER BLENDING TECHNIQUE
UPON ENGINE PERFORMANCE

| Mixing Method | None | Stirring | Ultrasonic | Homogenizer |
|---|---|---|---|---|
| Percent Water | 0 | 0 | 5 | 5 |
| Percent Emulsifier | 0 | 2 | 2 | 2 |
| Speed, rpm | 1600 | 1600 | 1600 | 1600 |
| Total Fuel Rate, kg/hr (lb/hr) | 17.9 (37.3) | 17.5 (38.4) | 18.6 (40.8) | 17.3 (38.1) |
| Combustibles Rate, kg/hr (lb/hr) | 17.0 (37.3) | 17.0 (37.4) | 17.0 (37.4) | 15.9 (34.9) |
| Power, kW (bhp) | 62.6 (84.0) | 62.5 (83.8) | 62.1 (83.3) | 58.8 (78.9) |
| Total Specific Fuel Consumption, kg/kW-hr (lb/bhp-hr) | 0.270 (0.443) | 0.279 (0.458) | 0.299 (0.490) | 0.294 (0.483) |
| Specific Base Fuel Consumption, kg/kW-hr (lb/bhp-hr) | 0.270 (0.443) | 0.272 (0.446) | 0.274 (0.449) | 0.269 (0.442) |
| Smoke, % Opacity | 29 | 30 | 29 | 24 |
| EGT, °C (°F) | 610 (1130) | 616 (1140) | 613 (1135) | 566 (1050) |
| NO, ppm | 549 | 566 | 485 | 462 |
| $NO_X$, ppm | 581 | 596 | 501 | 488 |
| CO, vol % | 0.26 | 0.25 | 0.27 | 0.21 |
| $CO_2$, vol % | 10.2 | 10.5 | 10.4 | 9.6 |
| UBH, ppm Carbon | 367 | 468 | 1116 | 1180 |

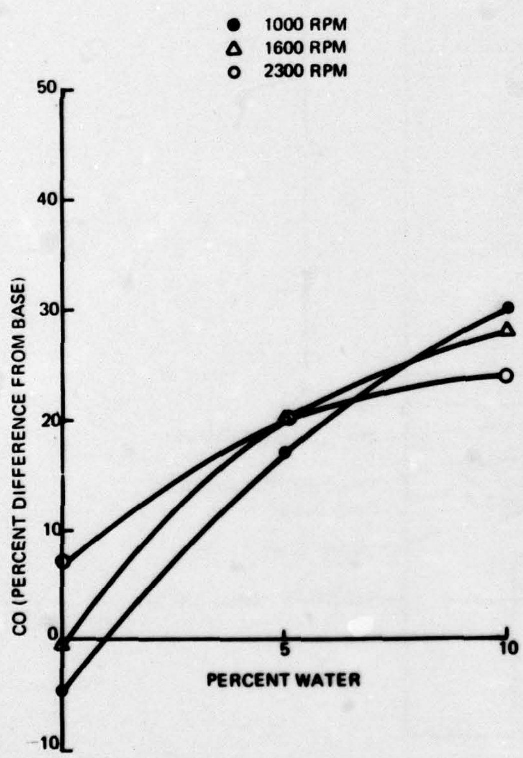



FIGURE 17. PERCENT CHANGE IN CARBON MONOXIDE EMISSIONS WITH WATER CONTENT

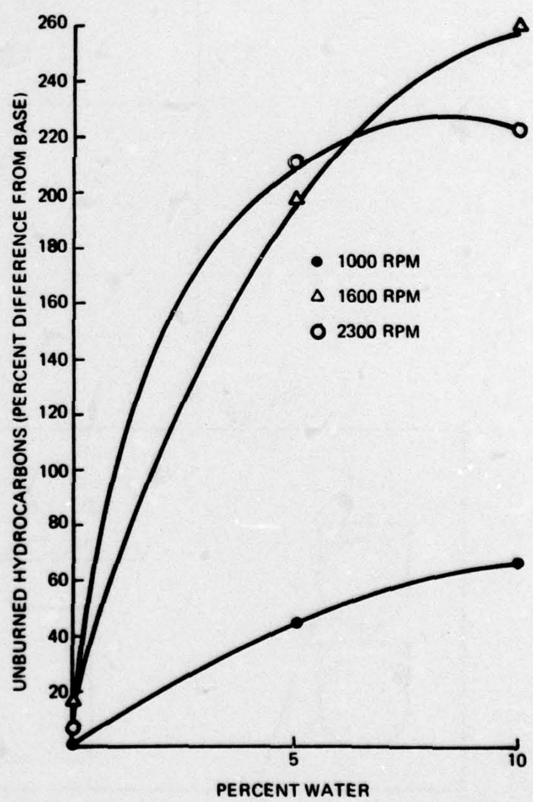



FIGURE 18. PERCENT CHANGE IN UNBURNED HYDROCARBONS EMISSIONS WITH WATER CONTENT

## IV. FUEL FIRE SAFETY IMPLICATIONS

AFLRL is conducting a fire-safety fuel development program for the U.S. Army, the purpose of which is to develop fuels which are much more fire resistant (or nonflammable) than present fuels except in the combustion chamber of an engine. The potential advantages of this type of fuel in a combat situation are obvious. This study has shown that diesel fuel containing a dispersed water phase exhibits enhanced fire-safety characteristics relative to those of neat fuel, particularly at temperatures above the base fuel flash point.

One of the techniques being used at AFLRL to evaluate fuel fire-safety properties is the previously described ballistic test. The test hardware is shown in Figure 19. The pictured drum contains fuel preheated to a given test temperature. The fireball and residual groundfire resulting when the actuator plate and drum are impacted with the 20-mm high-explosive incendiary tracer round are recorded by 16-mm color movies, high-speed color movies and black and white video tape recordings. When an incendiary ballistic projectile strikes a fuel tank, there are two distinct types of events that can be observed. Initially, there is a fireball that develops through the fuel mist cloud formed by the hot fragments of the projectile. This mist fireball, which has a duration of about a

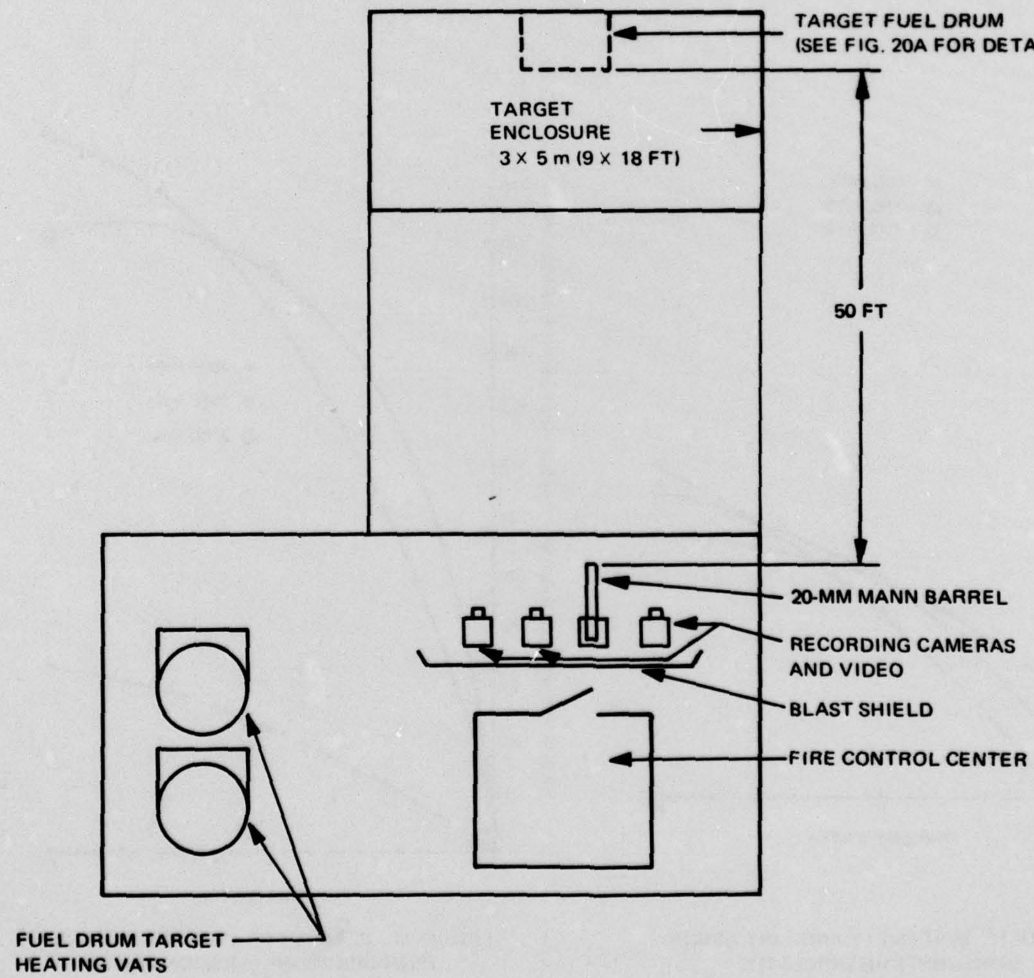



FIGURE 19. DIAGRAM OF SwRI BALLISTIC RANGE

second, can act as a secondary ignition source to flammables in close proximity of the penetration. Hence, if the sprayed/spilled fuel is above its flashpoint, the remainder (bulk) of the fuel will become involved in pool burning due to the fireball acting as an ignition source. It is this pool fire that usually causes overall loss of the vehicle.

A series of ballistic tests using the 10-percent water/fuel blend are illustrated in Figures 20 through 22. The test fuels were heated to 77°C (170°F). The neat diesel fuel (Figure 20) shows an extensive fireball followed by intense pool burning. This can be contrasted with the 10-percent water blend (Figure 21) at the same conditions. The water blend reduced the fireball size and duration, resulting in greatly reduced initial pool burning which subsequently self-extinguished. The third series of photographs show the same 10-percent water-content fuel at the same conditions, except that a 0.2-percent concentration of polymeric antimist additive had been included to control the mist fireball. As shown in Figure 22, the fireball was substantially reduced and no pool burning was observed, implying that the heat-sink properties imparted by the water eliminated the ground fire. Notice in the third photo that fuel is still spilling from the drum. In evaluating these results, it should be kept in mind that the 77°C (170°F) test temperature is 14°C above the fuel's normal flash point of 63°C (146°F), as indicated in Figures 20 through 22.

While this simple concept of dispersing water in a fuel appears to have tremendous potential as a means of drastically reducing fire vulnerability, very little is known about the mechanism actually involved in this inhibiting action. In fact, the various parameters used in preparing the emulsions appear to be significant when comparing the relative effectiveness of particular formulations. The most dramatic results obtained with a combination of 10-percent water and an antimist agent (Figure 22) further complicate the picture because even less is known that could explain why a combination of both water and antimist agent can eliminate both mist and ground fires at fuel temperatures well above the fuel's flash point. It is interesting to note that almost identical results were obtained with water-in-oil dispersions containing only 5-percent (vol) water, emulsifier, and antimist agent in the same base fuel.

## V. CONCLUSIONS AND RECOMMENDATIONS

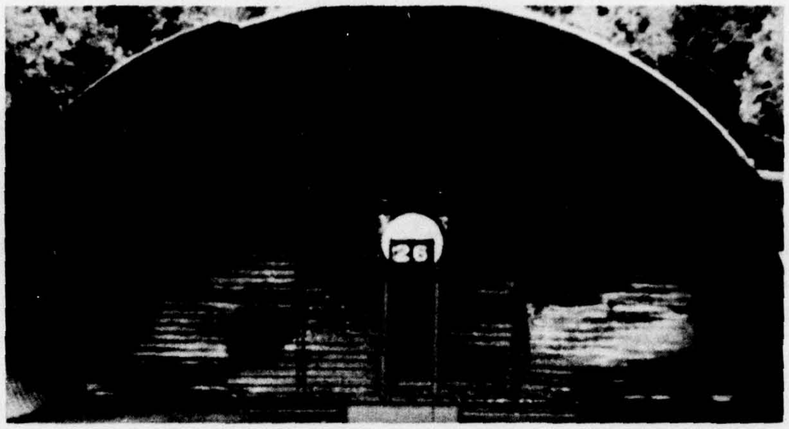
- Use of the described water/diesel fuel blends, with water concentrations of less than 10-percent, do not result in any significant loss of power at constant diesel fuel rate, when used in an unmodified LDT-465-1C engine.

- Use of the described water/diesel fuel blends in an unmodified LDT-465-1C engine does not improve nor harm the specific fuel consumption when only the diesel fuel is considered in the analysis. Therefore, the water emulsions do not appear to function as fuel extenders in this case.

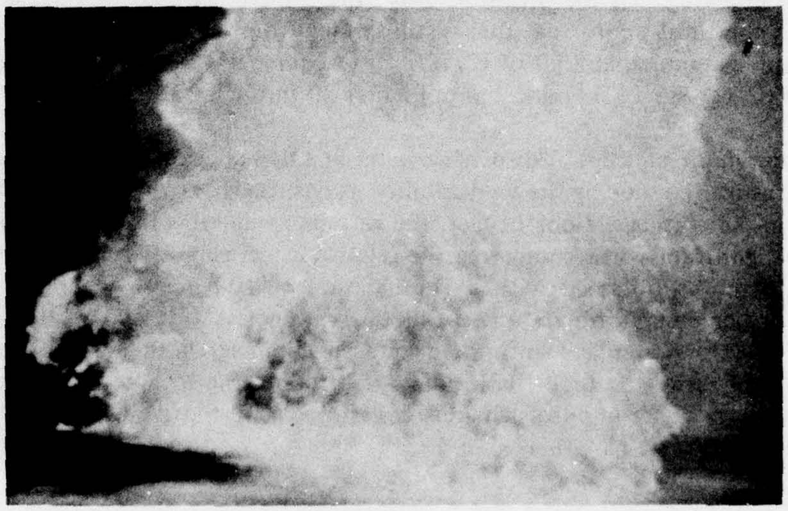
- Operation of an unmodified LDT-465-1C-powered vehicle on these emulsions would result in equal performance (except at full rack conditions) and would result in a reduction in the vehicle's range commensurate with the reduced volume of diesel fuel in the total fuel volume.

- Surfactant properties can have a significant effect on engine performance and emulsion stability. Additional studies using other surfactant compositions are therefore desirable.

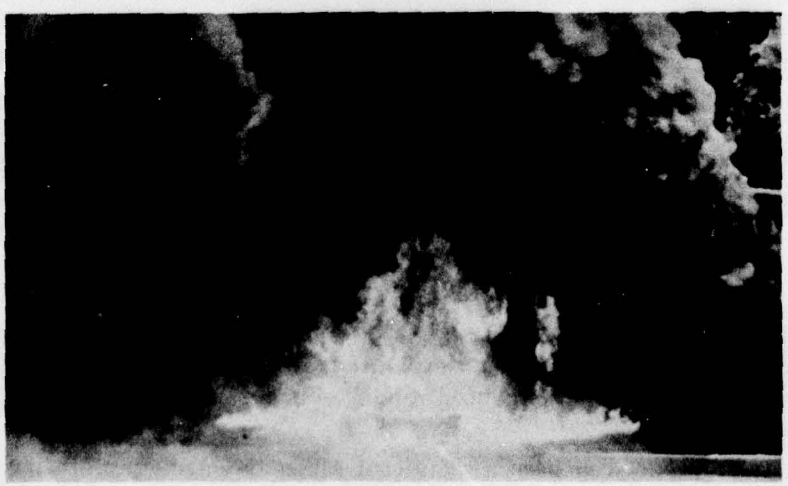
- The effect on visible smoke was not established. Additional research is necessary to better define smoke-reducing tendencies of various fuel/surfactant water blends.




*a. Neat Diesel Fuel at 77° C (170° F)*



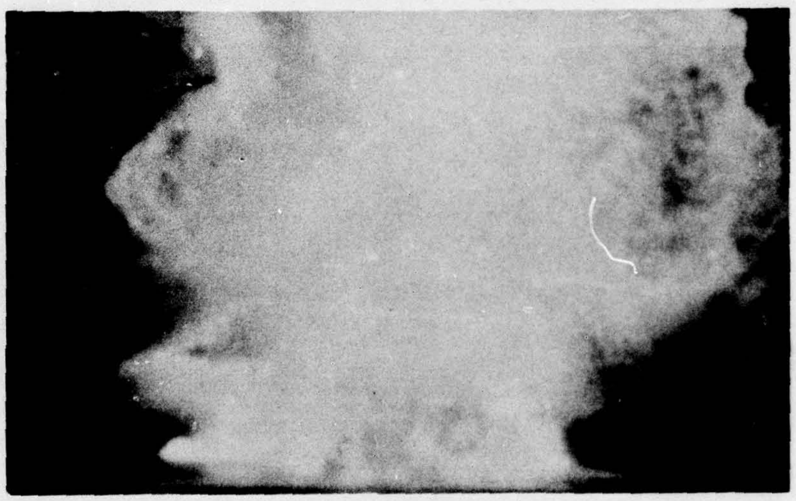
*b. Maximum Fireball; Neat Diesel at 77° C*



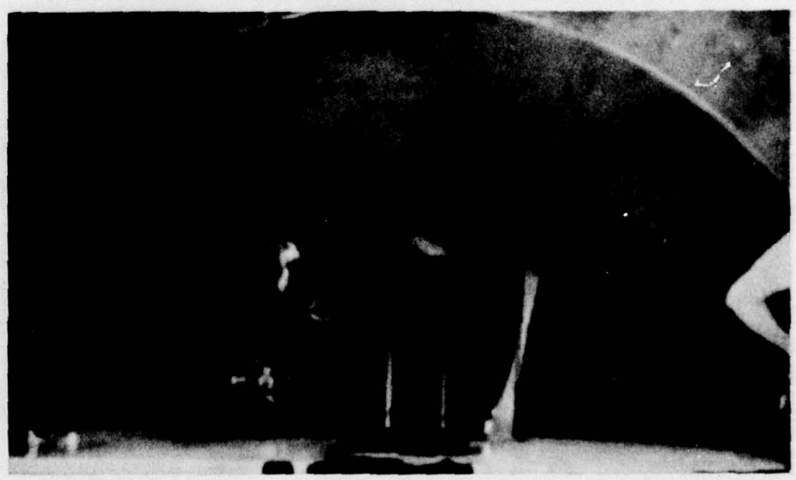
*c. Post-Impact Pool Fire; Neat Diesel Fuel*

FIGURE 20. BALLISTIC RESPONSE OF DIESEL FUEL AT TEST TEMPERATURE 14° C (25° F) ABOVE ITS FLASH POINT


*a. 10% Water Emulsion in Diesel Fuel at 77° C (170° F)*

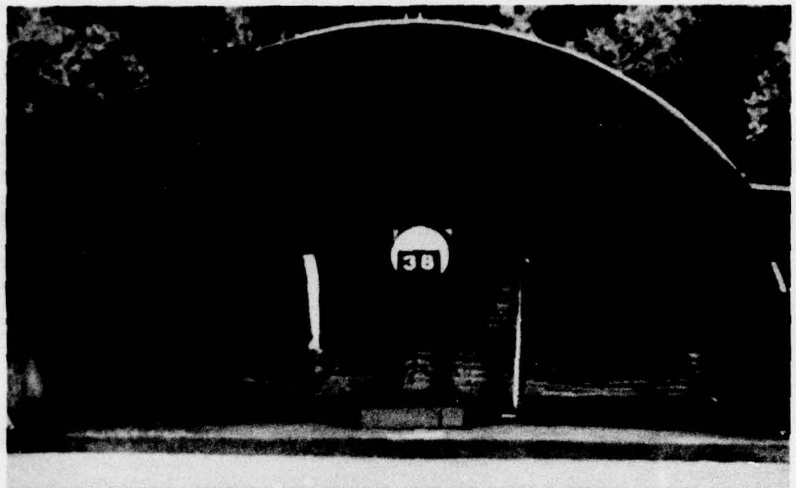


*b. Maximum Fireball; 10% Water Emulsion in Diesel Fuel*

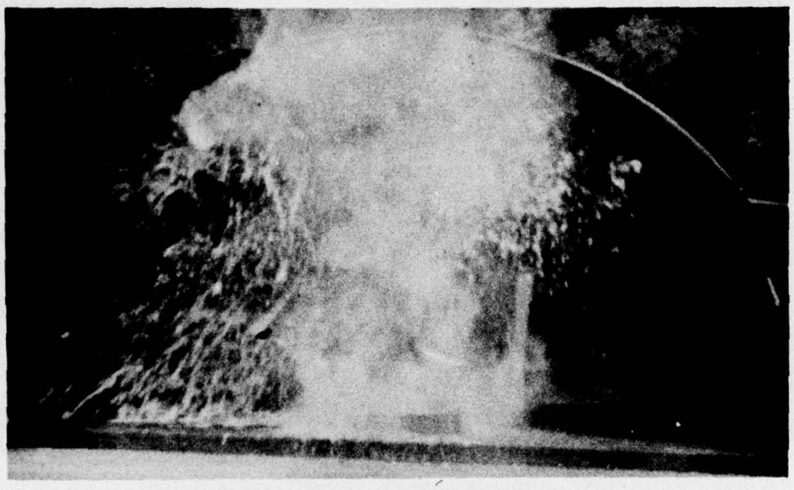


*c. Post-Impact Pool Fire; 10% Water in Diesel Fuel*

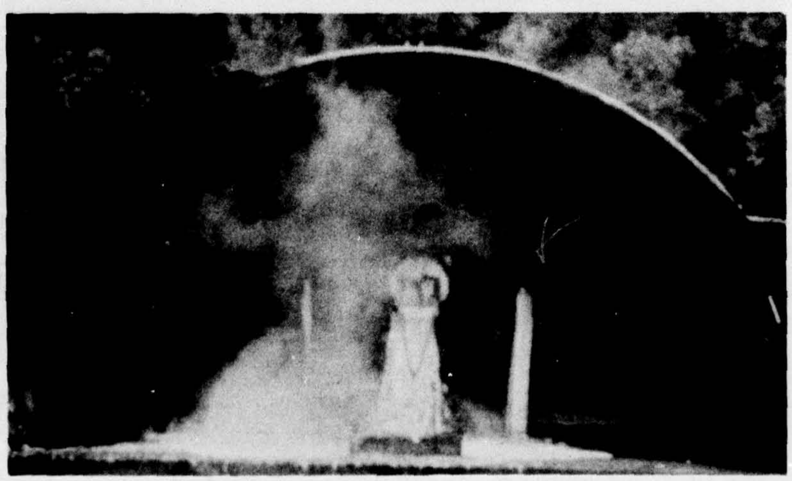
FIGURE 21. BALLISTIC RESPONSE OF HEAT-SINK FUEL AT TEST TEMPERATURE 14°C (25°F) ABOVE ITS FLASH POINT



*a. 10% Water; 0.2% AM-1 in Diesel Fuel at 77° C (170° F)*



*b. Maximum Fireball; 10% Water; 0.2% AM-1 in Diesel Fuel*



*c. Post-Impact Pool; 10% Water; 0.2% AM-1 in Diesel Fuel*

FIGURE 22. BALLISTIC RESPONSE OF HEAT-SINK FUEL CONTAINING 0.2% ANTI-MIST AGENT AT TEST TEMPERATURE 14°C (25°F) ABOVE ITS FLASH POINT

- Use of the described water/diesel fuel blends has a significant effect on non-smoke exhaust emissions. $NO_x$ is reduced while unburned hydrocarbons and carbon monoxide are increased, indicating increasingly incomplete combustion as the water content is increased.

- Further engine work in optimizing the engine/fuel combination must be conducted to define other potential benefits achievable through engine modifications. Effects of injection timing and fuel delivery rate in particular should be investigated.

- These water-containing diesel fuel blends have significant fire-resistant properties that, coupled with the lack of major performance deficits, make them very attractive candidates for reducing combat-related fuel fires. The fire safety aspects of these fuels should be further investigated to more completely ascertain the potential benefits.

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